Simultaneous wastewater treatment and biological electricity generation

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Abstract It is possible to directly generate electricity using bacteria while accomplishing wastewater treatment in processes based on microbial fuel cell technologies. When bacteria oxidize a substrate, they remove electrons. Current generation is made possible by keeping bacteria separated from oxygen, but allowing the bacteria growing on an anode to transfer electrons to the counter electrode (cathode) that is exposed to air. In this paper, several advances are discussed in this technology, and a calculation is made on the potential for electricity recovery. Assuming a town of 100,000 people generate 16.4×10^6 L of wastewater, a wastewater treatment plant has the potential to become a 2.3 MW power plant if all the energy is recovered as electricity. So far, power densities are low, resulting in power generation rates of ~ 150 kW/m^2. Progress is being made that we believe may result in as much as 0.5 MW from wastewater treatment. The generation of electricity during wastewater treatment may profoundly affect the approach to anaerobic treatment technologies used in wastewater treatment.

Keywords Electricity; energy; hydrogen; microbial fuel cell; wastewater

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Introduction

Aerobic treatment technologies continue to be a predominant form of wastewater treatment in the US despite rising energy costs. Conventional anaerobic treatment technologies are being increasingly used, but many wastewaters are too dilute to make current anaerobic treatment technologies, based on methane production, economical. The costs of wastewater treatment in the US are substantial, consuming annually $25 billion for all types of wastewater treatment (WIN, 2001). It is estimated that infrastructure costs during the next 10–20 years could require an additional capital investment of $45 billion. It is unclear how such large expenditures can be financed in the US, let alone in other countries with less economic resources. With over 1 billion people lacking adequate sanitation, new more affordable treatment technologies are needed.

It was discovered only a few years ago that electricity could be generated using bacteria in a microbial fuel cell (MFC) (Kim *et al.*, 1999). A MFC is fundamentally an anaerobic treatment process because the bacteria grow in the absence of oxygen in a chamber on an electrode. To generate electricity, the bacteria oxidize organic matter and pass the electrons to an electrode (anode). In this chamber there can be fermentation, but electricity is only generated when electrons are passed to the electrode. Protons are also created (maintaining a charge balance) and these protons must be able to migrate to the counter electrode so that they can combine with electrons and oxygen to form water. The generation of current, and the potential difference between the cathode and the anode chambers, creates the basis of the MFC. Overall, there is a maximum potential of 0.5–0.8 V, which is similar to that generated in a hydrogen fuel cell. This low voltage can be transformed to produce a higher voltage by connecting the reactors in series.

It should be realized that an MFC is a type of hybrid system—it is very different from traditional aerobic or anoxic wastewater treatment systems. At the microbial level, this is an anaerobic treatment technology. The bacteria must be grown in an anaerobic

environment in order to produce electricity. However, because oxygen is used at the cathode it is also an aerobic system, but the use of oxygen is not coupled to microbial respiration. If an air-cathode is used, no aeration of the wastewater is needed, saving costs compared to aerobic processes. The system needs to be designed to minimize oxygen leakage into the system, particularly across the cathode (air-cathode system) and the proton exchange membrane (aqueous cathode system), so that there is a minimal amount of aerobic treatment occurring unintentionally. However, even if oxygen does leak into the anode chamber it is rapidly consumed by bacteria in the anode chamber and thus a low redox potential is maintained.

In early studies the amount of current generated in microbial fuel cells was very low, but in the past few years there have been substantial increases in power generation. In this paper, I review findings by my research group at Penn State, with emphasis on the amount of power that can be generated from defined compounds and wastewaters. It is shown that power generation rates are constantly increasing, and therefore it can be expected that a wastewater treatment technology based on an MFC should be possible within only a few years.

Methods

Two-chambered MFC

The simplest type of MFC consists of two chambers separated by material that conducts protons between the chambers. The proton conducting material can be as simple as a salt bridge or even a porous ceramic plate. Ideally, the material should allow protons to diffuse between the chambers, but not allow substrate, bacteria or oxygen to move between the chambers. Proton exchange membranes (PEMs) developed for hydrogen fuel cells are optimal for this task, although they do allow oxygen to diffuse into the anode chamber. The electrodes can be made of any conducting, non-corrosive material. Depending on the system, plain carbon paper, carbon cloth, or graphite is used for the anode. The cathode must contain a catalyst for generating water from the protons, electrons and oxygen, and typically Pt is used and held on the carbon surface using a binder. The electrodes can be connected by any type of wire if the wire is not exposed to bacteria. Pt wire is the best choice, but it is expensive, so often copper wire is used with all surfaces coated with a non-conductive epoxy. Even if coated in this way, copper wire can be expected to eventually fail in the system. To avoid wires inside the chambers, the carbon electrodes can be extended outside the chamber and then a regular wire and clip can be placed on the electrode.

The electrodes are each placed into separate but adjoining chambers. The anode chamber contains the bacteria, and it is tightly sealed to prevent oxygen diffusion into the chamber. The headspace can be flushed with nitrogen gas to exclude air from the chamber. The cathode is immersed in water, and the water is bubbled with air (a typical aquarium air pump works well in the laboratory for this purpose). The ionic strength of the solutions in the two chambers should be matched. The anode chamber should contain nutrients (nitrogen, phosphorus and trace minerals) and biodegradable substrate. Details on specific media can be found elsewhere (Oh *et al.*, 2004; Logan *et al.*, 2005; Min *et al.*, 2005).

Single-chambered MFC

A simpler and more efficient MFC can be made by omitting the cathode chamber and placing the cathode electrode directly onto the PEM. This set up avoids the need to aerate water because the oxygen in air can be directly transferred to the cathode. Several designs are possible for this system. In the first design used in our laboratory, used to demonstrate

electricity generation from wastewater, the cathode was placed in the center of a cylinder, so that the anode chamber formed a concentric cylinder around the cathode (large SCMFC; Liu *et al.*, 2004). Graphite rods were placed inside the anode chamber, and these rods extended outside of the anode chamber and were connected to the cathode via an external circuit containing a resistor. Air was able to passively flow through the center tube so that it could react at the cathode. The Nafion membrane was hot-pressed onto the cathode, which was wrapped around a perforated plastic tube to provide support, with the membrane in contact with the solution in the anode chamber.

The second type of SCMFC was a single tube, with the two circular electrodes placed on opposite ends of the tube (small SCMFC; Liu and Logan, 2004). The end containing the anode is capped in order to prevent oxygen diffusion into the chamber, while the other end is open so that one side of the cathode faces air, while the other is bonded to the PEM and faces the solution in the anode chamber (Figure 1).

SCMFC lacking a proton exchange membrane

In many MFCs, a PEM is used for the reason that it has been used in hydrogen fuel cells. However, when water is used in the anode chamber, the PEM becomes unnecessary as the water will conduct protons to the cathode. The PEM may be a more efficient proton carrier than water, but the overall internal resistance of the system will be limited by proton diffusion in water—not in the PEM. In fact, the PEM may add to the internal resistance of the system. Therefore, the PEM has been removed in some studies in order to increase power output of the MFC (Liu and Logan, 2004; Liu *et al.*, 2005).

One limitation of the air-cathode systems is the potential for water leakage through the cathode. If a system is operated without the PEM, hydrostatic pressure can force water through the porous cathode. Water loss can be reduced by using a material, such as Nafion, as a binder for the catalyst (Pt) when preparing the cathode (Liu and Logan, 2004). Materials that can limit water permeability through cathodes in MFCs that lack PEMs are under investigation.

Results and discussion

Electricity generation from specific compounds

In our earliest studies, we examined electricity generation in a two-chambered MFC using acetate as the substrate for bacterial growth (Min *et al.*, 2005). In this system

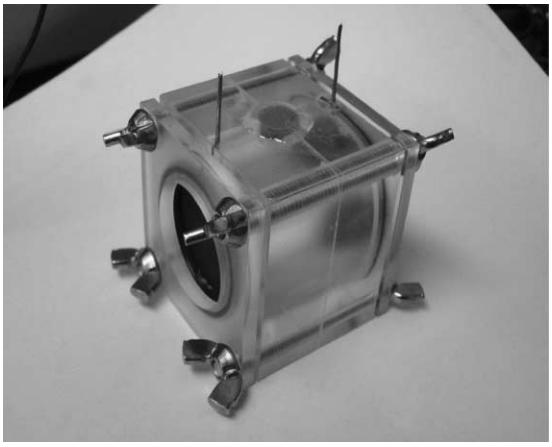

Figure 1 Small single-chambered microbial fuel cell (SCMFC) designed for laboratory tests. The circular carbon cathode is shown open to the air on the left, while the anode is on the opposite side and is covered. Two platinum wires extend from the top for electrical connections

the anode and cathodes were both made of carbon paper, with each electrode suspended in solution and contained in a separate bottle. The cathode contained a platinum catalyst. The two bottles were linked by a glass tube containing a salt bridge to conduct protons. This reactor was inoculated with *Geobacter metallireducens*, an iron reducing bacterium. We found power was generated on the order of ~1 mW, or less, per square metre of anode surface area (Min *et al.*, 2004). When the salt bridge was replaced with a more efficient PEM made of Nafion™, power increased to ~ 45 mW/m^2 (Min *et al.*, 2005). This level of power generation was similar to those reported by others for sediment-based MFCs and other laboratory systems using acetate or glucose as electron donors (Kim *et al.*, 1999; Bond and Lovley, 2003; Chaudhuri and Lovley, 2003).

In subsequent studies, we used mixed cultures in the MFCs. It was found that pure cultures were not needed, and that by using bacteria present in ordinary wastewater we could achieve power levels dependent on reactor configuration and operation, and not on the inoculum. When the two-chambered MFC of the type described above was inoculated with wastewater, similar power densities were achieved using the membrane MFC with either the pure or mixed culture (~40 mW/m^2). When a MFC was inoculated with a sea-water sediment (fed L-cysteine, an amino acid), power was generated in proportion to substrate concentration according to Monod-like kinetics (Logan *et al.*, 2005). Again, power densities were similar to that achieved with the pure culture. An assessment of the bacteria in the biofilm indicated a predominance of *Shewanella* species, although there were also many unidentified bacteria. We therefore concluded that inoculation of the reactor with ordinary domestic wastewater was sufficient to produce electricity in MFCs.

Using the direct-air cathode MFCs, we have found that we can produce higher power densities than that achieved with the two-chamber system. Tests using the direct-air cathode small SCMFC, with a PEM, produced 262 mW/m^2 using glucose (Liu and Logan, 2004). We have examined a variety of different substrates such as acetate, butyrate, and polysaccharides, and have shown that that previously attained power levels can be increased through more efficient MFC designs (Liu and Logan, 2004; Min and Logan, 2004).

By removing the PEM from a MFC, power generation levels using glucose were increased from 262 mW/m^2 to as much as 494 mW/m^2 (Liu and Logan, 2004). Glucose can be fermented to various end products, but when hydrogen is produced the main end products are acetate and glucose. Therefore, acetate and glucose were tested for power generation in this system. It was found that maximum power densities achieved in this PEM-less system were 506 mW/m^2 using acetate, and 305 mW/m^2 using butyrate (Liu *et al.*, 2005).

The advantage of the air-cathode (compared with the cathode suspended in water) is that oxygen transfer to the cathode occurs directly from air, and thus oxygen does not have to be dissolved in water. However, further increases in the performance of the cathode are needed to improve power output. For example, by using ferricyanide at the cathode instead of oxygen, and glucose as the substrate, it has been shown that power can be increased to as much as 3.6 W/m^2 (Rabaey *et al.*, 2003). Thus, this shows there is great potential to increase power densities in MFCs. However, such advances need to be made with renewable materials (i.e. not using ferricyanide) in order to make the process sustainable.

Electricity generation from wastewater

The greatest potential for the practical application of MFCs is in wastewater treatment. The observation that mediators (chemicals that shuttle electrons) did not need to be added into MFCs stimulated the development of MFCs for wastewater treatment. Liu *et al.*

(2004) demonstrated for the first time that electricity could be produced using ordinary domestic wastewater. In the large SCMFC they produced up to 26 mW/m^2 from continuous treatment of domestic wastewater. Not only was electricity generated, but up to 80% of the BOD was removed in the process. Power generation was in proportion to wastewater strength (COD), and was linear over the range examined. Thus, it can be expected that high power densities could have been achieved in this system with more concentrated wastewater. Removal of BOD was also proportional to detention time, with detention times of 12 hours typically used for this system. It was found that air did not need to be pumped through the cathode, and that passive air transfer to the cathode was sufficient for optimum performance of the system. The system contained a specific surface area (based on the anode) of 60 m^2/m^3 of reactor volume. Increasing the surface area of the electrodes will increase power output per volume of reactor, and should decrease detention times needed for wastewater treatment.

Further improvements have been made using domestic wastewater to increase power output (Table 1). For example, when the small SCMFC was used to treat wastewater, a maximum power output of 146 mW/m^2 was achieved with domestic wastewater in fed-batch tests (Liu and Logan, 2004). The increase in the power output was attributed to the reduced internal resistance of the small SCMFC compared to the larger system.

Economic implications of microbial POWER processes for wastewater treatment

The treatment of wastewater with electricity generation provides the basis of a new type of treatment system. In order to distinguish this type of system from other conventional treatment systems, we have begun to refer to this system as the microbial POWER (production of wastewater electricity reactor) system. This name conveys that bacteria are used in a wastewater system that results in power generation.

The economic potential for this type of treatment system for domestic wastewater can be examined, for example, on the basis of power generation from a town of 100,000 people. If we assume that there is 300 mg/L of BOD, and that 16.4 billion litres of wastewater are produced annually, then the potential exists for recapturing 2.3 MW of electricity (Table 2). With the earliest reactors, we could only capture a small fraction of this power, or 34 kW of continuous power. Because of the increases in power generation being made as this technology develops, a reasonable goal for power will be on the order of 1,000 mW/m^2 of reactor surface area. At this level, assuming reactor detention times comparable to those used today and reasonable energy recoveries, it is estimated that 0.5 MW of electricity could be produced. Assuming 1.5 kW per house needed for electricity (not including heating), 0.5 MW of power could produce electricity for 330 homes. If sold, the value of the electricity produced would vary considerably by location. For example, if we assume a typical low value of $0.05/kWh, this power would be worth $1

Table 1 Power densities achieved using a variety of complex wastewaters

Substrate	Power (mW/m^2)	Reference
Starch wastewater	19	Park *et al.* (2001)
	20	Gil *et al.* (2003)
Anaerobic sediments	16	Reimers *et al.* (2001)
	28	Tender *et al.* (2002)
Domestic wastewater		
Continuous – large SCMFC	26	Liu *et al.* (2004)
Flat plate	76	Min and Logan (2004)
Batch, small SCMFC (PEM)	28	Liu and Logan (2004)
Batch, small SCMFC (no PEM)	146	Liu and Logan (2004)
Animal wastewater	260	Kim *et al.* (2004)

Table 2 Electricity production from domestic wastewater, based on an assumed cost of electricity of $0.05/kWh or $0.44/kWh

Basis	First study	Goal	Max
Power-mW/m^2	26	1,000	–
Power- MW	0.034	0.5	2.3
No. houses	23	330	1,500
$0.05/kWh	$15,000	$569,000	$1,007,000
$0.44/kWh	$134,000	$5,000,000	$8,900,000

million annually ($US). Costs for electricity in North America are relatively inexpensive. Assuming an upper limit for this electricity in Europe, for example, at $0.44/kWh, the electricity would be worth $5 million. Clearly, this indicates that economic incentive to develop and adopt electricity production with wastewater treatment will vary.

Conclusions

The microbial POWER technology is still in an early stage of development, but shows great promise as a new method to accomplish both wastewater treatment and electricity generation. A key factor in future implementation of the technology will be the cost to build and operate the system. We do not yet know what the capital cost would be to build such a system as design improvements are still being made. However, we do know that it costs about $1000 per kW for capital costs to build a power plant. Thus, as we develop costs to produce electricity we can compare costs for a combined wastewater treatment/power generation facility in contrast to that needed for separate facilities. It is clear that combining wastewater treatment and power generation technologies will be both a challenging and rewarding engineering task.

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